

Vehicle Emissions and Life Cycle Analysis Models of Gasoline and Electric Vehicles

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ABSTRACT

In addition to air pollution emissions, the transportation sector in the US is responsible for more than 25% of greenhouse gas emissions. Due to the negative impacts of these emissions, primarily on health and the environment, literature of vehicle emissions models is rich. Yet, attempts to synthesize and contrast models of this rich literature are scarce. Contrasting models of gasoline and electric vehicle emissions could be particularly beneficial due to the significant differences between these two technologies; specifically with respect to emissions. Accordingly, this paper adopts a life cycle analysis approach to synthesize and explore the development and structure of some of the most common emissions models. The paper starts with a brief discussion of the emission models measurement techniques; then, explores and contrasts state-of-the-art vehicle emissions models. Four groups of emissions models are included in this synthesis: 1) Macro-scale models: MOVES2014 and EMFAC; 2) Meso-scale models: VT-Meso, MOVES2014, and MEASURE; 3) Micro-scale models: VT-Micro and CMEM; and 4) Electric lifecycle models: MOVES2014 and GREET. The paper highlights the effects of lifecycle analyses of both gasoline and electric vehicles on estimates of vehicle greenhouse gas emissions from each of these two technologies. The paper ends with a discussion of the shortcomings of current vehicle emissions models, limitations of their usage and application, and suggestions for future work.

1. INTRODUCTION

Over the last 60 years, the concern over greenhouse gas (GHG) emissions has increased. According to the United States Environmental Protection Agency (EPA), in 2012 28% of GHG emissions were produced by the transportation sector.¹ Beginning with the work of Arie J. Haagen-Smit in 1948, significant gains have been made in understanding the major sources of these emissions.² In 1963 the United States Congress passed the Clean Air Act, providing the framework for the first emissions control. Over the next 23 years, the Clean Air Act was amended and updated to account for developing research and technology.³ This legislation requires in part that vehicle emissions models be created and subsequently updated to aid in the estimation and controlling of emissions. Large efforts have now been made to model how vehicles produce these emissions for the ultimate purpose of making vehicles more efficient. Vehicle emissions models can be split into four main categories: macro, micro, meso, and life cycle. The following sections present the prominent models that are found in current literature for each of these categories. This paper is organized as follows: Section 2 contains a brief discussion of various vehicle emissions data acquisition techniques. Section 3 discusses the various vehicle emissions models used for the macro, micro, and meso categories, specifically

focusing on the approaches used in vehicle emissions predictions as well as strengths and weaknesses of each model. Section 4 expands this discussion into life-cycle analysis models, noting the affects this type of analysis has on emissions. The paper then ends with some concluding remarks and recommendations for future work.

2. VEHICLE EMISSIONS DATA ACQUISITION

2.1 LABORATORY DATA ACQUISITION

Nearly every emissions model is created based on a combination of laboratory and field measurements. In laboratory tests, vehicle emissions for various makes and models of vehicles are measured using a chassis dynamometer. This tool connects directly to the engine's crankshaft and provides resistance either through a magnetic field or a water chamber. Dynamometers can be calibrated to offer a specific amount of resistance to simulate factors such as friction, wind, and sloped surfaces. During the test, the engine is run under a specific load cycle - a predetermined sequence of accelerations, cruises, and idle periods. While the test is running, emissions produced by the engine are collected and analyzed.^{4, 5}

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Laboratory tests are done in a controlled environment and allow vehicles of different makes and models to be subjected to the same loading situations. This in turn produces results that are relatively easy to compare and correlate. However, laboratory tests suffer from a major flaw. They often misrepresent short-term events such as rapid accelerations and unusual driver behavior. To solve this problem, many models also use field measurements to supplement data obtained in the lab.

2.2 FIELD DATA ACQUISITION

Field measurements are done using On-board Emissions Measurement Systems (OEMS). These systems connect to the vehicle tailpipe and the On-Board Diagnostic System (OBD).⁶ Emissions are collected from the tailpipe and the instantaneous speed and acceleration are recorded through the OBD. OBDs come in various sizes depending on the type of vehicle being analyzed. These proportions range from the size of a large backpack to the size of a small car. Other measurement methods include power-train tests and remote sensing techniques.³

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3. EMISSIONS MODELS

As stated above, vehicle emissions models can be split into four main categories: macro-, meso-, and micro-scale, as well as life cycle analysis. Each of the first three scales encompasses a certain scope. Macro models examine regions of area in a transportation system. These models are not concerned so much with individual emissions from vehicles, but with the target area as a whole.^{7, 8} Micro models are the opposite and focus on emissions from vehicles on an instantaneous basis based on the speed and acceleration of the vehicle.⁷⁻⁹ Most often, they are used to predict the amount and nature of the emissions at specific points or intersections along transportation links. Meso models are a mixture of these two and typically involve a specific link or traffic analysis zone of the transportation system.^{7, 8} During the development of these models, the type of data required depends on the model and on the eventual purpose of the analysis. In

this section, the design of macro models will be discussed and will be expanded in the following subsections to address micro and meso models.

3.1 MACRO VEHICLE EMISSIONS MODELS

Macro vehicle emissions models have historically been the fastest and simplest way of obtaining estimates of vehicle emissions. Macro models require far less data inputs than other scales, and due to their relatively basic structure and straightforward way of calculating emissions, they are able to quickly return estimates. Though there are a large number of models that are currently used, this paper will focus on the two major models found in literature: the MOVES and EMFAC models.

3.1.1 MOVES MODEL

Beginning in 1970, the United States EPA began developing a macro vehicle emissions model to serve as a tool when evaluating whether states or agencies were conforming to provisions of the Clean Air Act.¹⁰ The EPA currently uses two macro emissions models: the MOBILE model and its replacement, the MOtor Vehicle Emissions Simulator (MOVES). Because the MOVES model has replaced the MOBILE model, the design of the MOVES model will be discussed here. The MOBILE model still serves as a base platform for many countries seeking to establish their own macro emissions model, but the development of the MOBILE model is not significantly different from the MOVES model. As noted above, macro models deal with large geographic areas and so do not require instantaneous speed and acceleration data. Instead the MOVES model operates on what the EPA calls “total activity”. To calculate this parameter, the MOVES model first divides vehicle uses into categories, using terrain (e.g. rolling, flat) and location characteristics (e.g. urban, rural). Next, the vehicles being analyzed are sorted into each of these usage categories. Finally, the model calculates how long each of these vehicles spends traveling while in their given category.⁷ Using this approach, vehicles that have long commutes will have a greater total activity than those with short commutes. Also, vehicles that travel in rough terrain will have greater total activity than those in mild terrain.

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The total activity calculations are primarily based on data that the EPA has itself collected over decades of testing vehicles and from other agencies such as the California Air Resources Board and various automobile manufacturers. This data is subdivided into various categories based on the make and model of the vehicle as well as the model year. Additional attributes of the data include terrain location and operating time.¹¹

Notice, however, that in the EPA’s definition of total activity that the terminology is “the population” of a given vehicle/use type. This refers back to the fact that MOVES used to primarily be a macro-scale model, utilizing a large number or population of vehicles. It involves a direct relationship between total activity and total emissions. The more activity a vehicle undergoes, the more emissions are produced. For counties and large areas, this is an ideal type of analysis. It is too expensive in most cases to collect emissions data for every type of vehicle traveling in a region. Instead, the percent distribution of vehicle types and terrain can be determined through such things as existing databases or vehicle registration information. This

information can then be used in the MOVES model which will link the information with previously tested vehicles of the same make and model that travelled over similar terrain.

This process is best illustrated by an example input into the model. Suppose a user wants to determine the emissions in a particular city having a population of 200,000. From the city's vehicle registration information, it is discovered that passenger car model years range from 1968 to 2015 and that vehicle makes range between 12 different manufacturers. The terrain of the city is primarily asphalt paving having average speed limits between 20-45 mph. The user can simply determine distributions for each of these areas and input the data into the MOVES model. For instance, perhaps 10% of the cars are 1968-1975 models, 24% are 1976-1987 models, 39% are 1988-2000 models, and 27% are 2001-2015 models. Furthermore, suppose that the car population is equally distributed between the different manufacturers and between the different speed ranges. Each of these distributions is linked to past data for that particular make, manufacturer, model year, speed, etc. Combining all this data, the total emissions are then calculated.

3.1.2 EMFAC MODEL

Another macro-scale model currently in use is the California Environmental Protection Agency, Air Resources Board's (CARB) Emission FACTors Model (EMFAC). This model is structured in many ways like the MOVES model. Drawing from a large database obtained from Department of Motor Vehicle records, Smog Check reports, and other sources, the EMFAC model uses this information to calculate emissions factors that are multiplied by the source activity of a vehicle. The processes behind these calculations are identical to those used in the development of the MOVES model. During the creation of the EMFAC model, data regarding each vehicle process of concern was evaluated and a correlation was made. Using this correlation, the emissions for a given vehicle can be predicted, just as in the MOVES model.¹²

The major differences between the MOVES and EMFAC models are in their structure and scope. The MOVES model is intended for use as a comprehensive, single unit. The EMFAC model, on the other hand, is a composition of several smaller modules. The modules currently divide the model into three portions: light-duty vehicle analysis, heavy-duty vehicle analysis, and transportation planning analysis. By splitting up these functions, the EMFAC model both provides a more direct approach to analysis and also allows its developers to easily add new modules in the future should the need arise.¹³

Macro models are best when dealing with large populations of vehicles. Nevertheless, an interesting and powerful function of the MOVES and EMFAC models is that they can be used to predict vehicle emissions on both the meso and micro-scales. The same process that is described above can be used for intersection and street level analyses simply by using a different distribution of vehicle makes, models, and roadway speeds.

3.2 MICRO VEHICLE EMISSIONS MODELS

The necessity of having a micro vehicle emissions model began in 1990 with the passage of a set of amendments to the Clean Air Act. These amendments required in part that

organizations provide plans that detail the impacts of transportation projects and improvements on air quality. Signalized intersections, highway on-ramps, and other small scale projects suddenly required a means of estimating future emissions.

Two micro emissions models came into being to fill this need. These were the Comprehensive Modal Emissions Model (CMEM), developed by the University of California, Riverside, and the Virginia Tech Microscopic energy and emissions model (VT-Micro). Both of these models accomplish the same relative purpose, but tackle the problem in slightly different ways.

3.2.1 THE COMPREHENSIVE MODAL EMISSIONS MODEL (CMEM)

The CMEM model was developed by the University of California, Riverside to predict emissions for light-duty vehicles (i.e. automobiles and small trucks) under various operating conditions.¹⁴ It is one of the most widely used micro-scale models and was created by breaking the vehicle operation and emissions cycles into six categories: engine power, engine speed, air-to-fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction.¹¹ The calculation of emissions from each of these categories is determined using variables such as the vehicle speed and acceleration and the grade of the roadway. This information is potentially available from sources such as the EPA database. The emissions calculations also use constants in the form of calibrated parameters. These include such things as the engine friction factor and cold start coefficients.¹⁵ These constants are preset to default values in the core model, but can easily be adapted to fit the context and particular parameters of a given situation.

During the development of the CMEM model, over 300 vehicles were tested in the laboratory on a second-by-second basis using three different drive cycles. Both engine-out emissions (emissions originating directly from the engine) and tailpipe emissions were measured.¹⁵ This data was used to create a power-based model, basing emissions off of the predicted power usage of the vehicle. The CMEM model calculates emissions using the process illustrated in the following figure.

3.2.2 THE VIRGINIA TECH MICROSCOPIC ENERGY AND EMISSIONS MODEL (VT-MICRO)

The VT-Micro model was originally developed in the early 1990s using emissions data from nine light duty vehicles. In 2002, this data set was expanded to include tests from 60 vehicles.¹¹ Like the CMEM model, inputs to the VT-Micro model include the instantaneous speed and acceleration of the vehicle. However, the VT-Micro model uses a non-linear regression structure in place of a power-demand model. One of the major defects of the CMEM model is that it returns the same emissions estimate for situations in which the amount of applied power is the same. For example, a vehicle may use the same amount of power driving 60 mph in flat terrain as it would driving at 20 mph on a steeply sloped road. The actual emissions produced in these situations may be very different, but since the CMEM model uses power to calculate emissions it returns the same emissions estimate for both cases. Using a regression analysis, the VT-Micro model solves this problem by relating emissions estimates to the instantaneous speed and acceleration of the vehicle, rather than to power.

Another problem with the CMEM model was that it estimated a constant amount of emissions whenever a vehicle experienced negative acceleration. As has been shown in numerous tests, the emissions curve is in fact variable during these decelerations. To address this issue, developers of the VT-Micro model used two separate mathematical formulae to estimate emissions – one for positive accelerations and another for negative accelerations. These formulae have the same form and vary only in the regression coefficients used.⁹

It is important to note that while the CMEM model takes into account the vehicle operating condition, such as the power demand and condition of the engine, air/fuel ratios, and enrichment and lean conditions, the VT-Micro model has no such analysis, relying instead on empirical data that leads to generalizations and simplified processes. This is both a benefit and a disadvantage of the VT-Micro model. The benefit is that the VT-Micro model is much simpler in its structure and abnormal emissions behavior can easily be traced back to the source. The disadvantage is that in situations where the vehicle is in disrepair (e.g. deteriorated or malfunctioning engine), the VT-Micro model may underestimate the emissions produced.¹¹

3.2.3 MOVES AND EMFAC MODELS

As noted earlier, both the MOVES and EMFAC models have the capability to be used in micro emissions models. The approach used in each of these models is the same as that used in the macro-scale analysis. The only difference is in the input parameters required. For instance, when the MOVES model is used for macro-scale analysis, instantaneous data is ignored and average speeds and distances are used instead. When used in micro-scale analysis, however, the instantaneous speed and acceleration of a vehicle are necessary inputs. Nevertheless, the process that each model goes through to estimate emissions on a micro-scale is exactly the same as that discussed earlier in Section 3.1.

3.3 MESO VEHICLE EMISSIONS MODELS

Every model is originally designed to serve a specific purpose. For macro-scale emissions models, the goal was to provide estimates for large geographical areas using easily obtained data. Micro-scale models came about with the advent of traffic simulation programs and the Clean Air Act Amendments of 1990. The need arose to model emissions accurately on a small scale for a particular intersection, ramp, or roadway. In many cases, though, there is either an inability to collect enough data for a microscopic analysis or a lack of time to collect and evaluate this data. In these situations, macro models were used to model the emissions, but this resulted in estimates heavily prone to error. The macro models simply did not have enough parameters to accurately predict the emissions on a microscopic scale. Researchers began to merge the macro and micro models together, forming models that were less data intensive than micro models, but still maintained a high level of accuracy for small scale analysis. There are currently three main meso models mentioned repeatedly throughout literature, the VT-Meso, the MOVES model previously mentioned, and the MEASURE model.

3.3.1 THE VIRGINIA TECH MESO MODEL

The VT-Meso model uses an approach similar to the VT-Micro model, estimating emissions using a non-linear regression model. However, instead of the basic input parameters being instantaneous speed and acceleration, in the VT-Meso model the basic inputs are average vehicle speed, number of stops made, and stopped delays for a given link or intersection. Using these inputs, the model creates a synthetic drive cycle and determines the amounts of time a vehicle would spend accelerating, decelerating, idling, and cruising. These values are then used in a series of mathematical formulae that allow the user to predict the amount of fuel consumption and emissions produced.¹⁶

3.3.2 THE MOVES 2014 MODEL

The MOVES 2014 model uses a different approach to estimate emissions on a meso-scale. As discussed in previous sections, this model is also commonly used in macro-scale analysis. Its approach to both scales is the same. In both macro and meso-scale analysis, the MOVES model separates the vehicles operation into different operating modes based on a wide variety of parameters including speed, acceleration, and road grade. Once this is done, the total activity of the vehicle is calculated and then compared with historical data. Using this comparison, estimates are made for the amounts of emissions produced. Additional input parameters that are required for meso-scale analysis (in addition to those required for macro-scale analysis) include vehicle miles travelled (VMT), road type, age of the vehicle, speed distribution, meteorological data, and vehicle type.^{11, 16} These extra parameters help the model generate more accurate estimates for the vehicle's emissions.

3.3.3 THE MEASURE MODEL

The Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) model uses an empirical statistical approach to estimating emissions. Originally created for use with GIS systems, the MEASURE model uses vehicle registration data, travel-demand forecasts of flows, speed and acceleration distribution tables, and socioeconomic data as inputs. From these the model can predict congestion levels and the distribution of modal activities. Finally, the model uses these values to create emissions estimates for each link or zone being evaluated. In many ways, the approach of the MEASURE model is comparable to the MOVES model. Both separate vehicle activities into various operating modes and then use comparisons with past data to generate emissions estimates. The advantage of the MEASURE model, however, is that it is less biased than other models. Because its approach is statistical, it chooses the most probable values for emissions estimates, rather than averages or most frequently occurring values.¹⁷

3.3.4 COMPARISON OF MESO MODELS

All three of these models have their own set of advantages and disadvantages. The VT-Meso model requires very few inputs and is therefore a relatively simple model to use. In addition, it was calibrated to return the same emissions estimates as the VT-Micro model for a given vehicle. Because of this, there exist strong correlations between the VT models. A significant disadvantage of the VT-Meso model, though, is that it assumes constant accelerations and decelerations throughout the drive cycle (Figure 2). Careful efforts have been made to ensure

that despite the obvious differences between the actual and synthetic drive cycles, they are equal in terms of fuel consumption and emissions produced. Nevertheless, because of the averaging process involved in this model, it may under or overestimate emissions for erratic driving behavior situations.

The EPA's MOVES model's strength lies in its extensive inventory and database information. It has the ability to estimate emissions for dozens of vehicle modes (which are determined – among other things – by speed, acceleration, and road grade), providing far more flexibility than other models. In fact, its inventories of data are used by nearly every research facility developing new emissions models in the United States. The MOVES model has an easy-to-use interface and requires data that can be obtained from a traffic demand model of the area in question. The problem with the MOVES model is that it uses a comparative process for emissions – taking data from tests of similar vehicles and using that data in equations that model vehicle operating processes.¹⁸ While this makes the model very efficient for most vehicle scenarios, it also causes the model to have trouble in accurately predicting emissions for situations in which there are significant amounts of time spent in acceleration and deceleration. In these situations, the VT-Meso or MEASURE models would be better choices for emissions estimation. Keep in mind, however, that the MEASURE model was specifically designed for use with a GIS database.¹⁶ In order to take advantage of the MEASURE model's statistical approach, source data may have to be converted into an acceptable format.

4. LIFE CYCLE ANALYSIS

Life cycle analyses (LCAs) came into existence long before the creation of vehicle emissions models. This type of analysis examines the entire life of the vehicle, beginning with the extraction of the fuel source and continuing through the manufacture, use, and disposal of the vehicle. Though life cycle analyses are used for a broad range of applications, for the purpose of this paper we will limit our discussion to life cycle analysis as it applies to modeling vehicle emissions for both gasoline and electric vehicles. In vehicle emissions modeling, the life cycle analysis process covers five main areas: raw material acquisition/procurement, material processing, vehicle assembly, vehicle service life or use of the vehicle, and the recycling/disposal of the vehicle, as shown below (Figure 3).¹⁹ These areas are examined briefly below.

4.1 OVERVIEW OF VEHICLE EMISSIONS LIFE CYCLE ANALYSIS

The raw material extraction phase of a LCA involves determining the amount of emissions generated by the collection of fuels, metals, chemicals, and other resources as they exist in their natural state in, on, or above the earth. After their extraction, these materials are then transported to industrial facilities. Once the raw materials reach the industrial facilities, they enter the materials production phase in which they are refined and processed for subsequent use in the construction of the vehicle. Also included in this phase are the production of batteries, engines, motors, and the generation of fuel or electricity. The next phase in LCAs is vehicle production. This phase could perhaps be better labeled as vehicle assembly and testing as it involves the actual construction of the vehicle using the materials produced in the previous phase. Following this is the service life of the vehicle. This is itself a collection of other subgroups including the maintenance, use, and storage of the vehicle. Many life cycle studies

end their analysis after this phase, choosing to ignore the disposal or recycling of the vehicle components because of the variability of emissions involved in this last phase. This type of study is a subset of LCAs and is commonly called a “Well-to-Wheels Analysis”. LCAs that do include the final phases treat recycling as the removal of any parts or components that can be reused or salvaged. Most of these recycled materials are reincorporated into the materials production phase as shown in Figure 3. For all of the components that are either too expensive or impossible to recycle, such as vehicle batteries, the only option left is to dispose of them. This constitutes the final phase of LCAs and though often ignored, can greatly affect the long term sustainability of a particular design or solution.

LCA models in literature are not consistent. As mentioned above, though a comprehensive LCA model should include all five stages, most do not. For example, in addition to “Well-to-Wheels Analyses”, researchers will also refer to a “Pump-to-Wheels Analysis”, also called a “Tank-to-Wheels Analysis”. This also is not a true life cycle analysis and only examines the service life phase. Beginning with the moment fuel is pumped into a vehicle, the emissions are measured and recorded. It is this type of analysis that is currently used when modeling gasoline vehicle emissions. All of the emissions models discussed so far have been “Tank-to-Wheels” analyses and as has been shown the models differ both in their scope and in their approach to modeling in-vehicle emissions for gasoline vehicles.

When constructing electric vehicle emissions models, the standard approach of using a Tank-to-Wheels analysis is not as beneficial. Though Tank-to-Wheel studies are still used to determine in-vehicle emissions, these analyses are mostly done as part of an LCA. The necessity for using a LCA is that electric vehicles essentially produce no tailpipe emissions. The service life of an electric car therefore produces only a very small effect on the overall emissions produced by electric vehicle. The primary LCA model found in literature is the GREET model. It is important to note that although some models such as MOVES and EMFAC can evaluate emissions from electric or hybrid vehicles, they can only evaluate the service life phase. The GREET model is therefore the only model addressed in this paper that performs a full LCA.

4.2 THE GREET MODEL

The foremost and most significant life cycle analysis model for both electric and gasoline vehicles is the GREET Model, developed by the U.S. Department of Energy at the Argonne National Laboratory. Much like the MOVES model discussed earlier, the GREET model calculates emissions using factors determined based on the pathway being analyzed. In this case, a pathway can be best defined by an example. Taking the six stages of a LCA, imagine that the lithium for a battery was extracted by a mining process, was transported by truck to a refining plant, and was then refined using electrolysis. Next, suppose that the refined lithium is used to construct a lithium-ion battery that will be later installed in a vehicle. Once the installation is complete, the finished vehicle is transported by air and then truck to a sales location where it is sold. The vehicle is then used for many years until it is no longer functional. Each of these steps of the LCA together make up a single pathway. If even just one phase of the LCA was changed, such as transporting the raw material by freight train instead of truck, then it would result in a completely different pathway.

As can be seen, there is a vast multitude of possible pathways that the GREET model uses. The materials transportation phase alone can happen in many different ways, such as through the use of trucks, rail cars, ocean liners, barges, air freight, or pipelines.²⁰ In the GREET model, each of these travel modes has a separate emissions factor associated with it. In the same way, each manufacturing process has a separate emissions factor associated with it. This method of analysis is repeated through all the different aspects of the vehicle pathway, with each phase yielding a separate emissions factor. These emissions factors are then combined and used to calculate the total emissions produced during the life of the vehicle.

It is important to draw a distinction at this point between the gasoline vehicle emissions models discussed in Section 2 of this paper and the GREET model. Previously, the models used input parameters in the form of such things as instantaneous data or total activity. For the GREET model, input data is in the form of average vehicle speed, the type of load the vehicle is transmitting, and the total vehicle miles travelled.²⁰ This approach is similar to a macro-scale approach to emissions estimates. However, most macro-scale models like MOVES and EMFAC take into account several additional parameters like terrain type or speed distribution. Because GREET uses a more general approach, it tends to be less accurate when it comes to in-vehicle emissions estimates. Nevertheless, this is not usually a problem for researchers since the GREET model is most often used for analyzing electric vehicles. Since electric vehicles produce almost no emissions during the service life phase, this inaccuracy is not usually a problem.

Another observation of the GREET model is that although claimed to be a comprehensive LCA model, it does not predict emissions for the recycling or disposal phases. The GREET model can only predict emissions for the first four phases of an LCA and could therefore be better labeled as a “Well-to-Wheels Analysis” model rather than a comprehensive LCA model.

4.2.1 GASOLINE VEHICLE EMISSIONS MODELING

The GREET model can also be used to calculate life cycle emissions estimates for gasoline vehicles. Its approach for these vehicles is exactly the same as that used for electric vehicles. Incorporated into the GREET model are petroleum collection and refining stages that are further subdivided to take into account the production and use of diesel vehicles. The model uses these stages to determine emissions factors and then uses the factors to estimate the overall emissions produced during the life of the vehicle – just like it does for electric vehicles.

Perhaps the most important aspect of the GREET model is that it places a significant amount of weight on where a particular material is collected and transported from. For instance, the crude oil for petroleum fuel can be from Alaska, Canada, Mexico, etc. Each of these locations produces a slightly different type of oil that requires its own unique set of transportation and treatment processes. In addition, the transportation distance from the point of collection to the point of refinement varies depending on the collection location. All of these factors affect the emissions calculations for the raw material extraction and material production stages of the life cycle analysis.

4.2.2 ELECTRIC VEHICLE EMISSIONS MODELING

For electric vehicles, the collection, transportation, and treatment of different fuel sources is even more important. Electricity production is often classified using a specific type of grid. These grids are classified based on what natural resources are used to produce the electricity. These natural resources include coal, wind, hydro, nuclear, biomass, natural gas, and oil among others. Each state has its own particular grid based on the facilities that supply it. The national average grid distribution for the United States is shown below to illustrate the sources that might be found in a given state (Figure 4).

Though the grid for each particular area varies significantly, large areas are typically generally classified by a single grid.²⁰ The significance of this grid production in LCAs is that each fuel creates a different amount of emissions. Coal plants and oil refineries typically give off far higher levels of emissions compared to wind farms or hydroelectric generators. It is important to realize then, that the results of LCAs are not uniform, but can vary for the same vehicle depending on where it was produced and where it receives its fuel from.

5. RESULTS

As with all vehicle emissions models, future emissions are calculated based on past results. The main differences between macro, meso, micro, and life cycle models are the data they use and the equations they use to represent that data. In macro models, it is a direct relationship. The more activity a vehicle undergoes, the more emissions it will produce. In meso models, a direct relationship is also used, but the inputs are changed to permit greater accuracy. In micro models, regression curves are typically used and the data is based on the speed and acceleration of particular vehicles, rather than total activity or average speed. This in turn allows for even more precise predictions to be made. Life cycle models like GREET also use a direct relationship to model data, using a single combined emissions factor to generate emissions estimates.

Clearly, the scope and method of estimation for various models varies significantly. However, the question still remains, which one is best? The answer depends on the application. Table 1 below gives a brief synopsis of each of the models discussed above along with their major strengths and weaknesses. Three primary observations can be made regarding the models discussed above. The first is that no single emissions model should be used for every situation. Every model that is developed has its own set of strengths and these should be utilized to their maximum potential. A careful examination of the various models available should be made before any analysis is done to ensure that the model meets the accuracy and application requirements of the user.

A second observation that can be made is that almost all emissions models for petroleum-fueled vehicles use a Pump-to-Wheel analysis. Thus, the outputs will only reflect the in-vehicle emissions that are produced. Emissions models for electric vehicles, on the other hand, vary between Pump-to-Wheels analyses and life cycle analyses. This should be kept in mind when examining the results of any emissions estimation. It is a common mistake to compare the emissions of gasoline and electric vehicle with little regard to the type of analysis used. Electric

vehicles are often hailed by consumers and popular media as the perfect alternative to gasoline powered vehicles. An uninformed user may tend to believe that electric vehicles produce almost no in-vehicle emissions and compares this with normal, gasoline vehicles. In this comparison, the user will find the electric car to be vastly superior. However, this type of analysis ignores a major factor. The bulk of electric vehicle emissions are not produced during vehicle operation, but rather during the production and assemblage of the vehicle, as well as the extraction and processing of the vehicle's fuel. If a user wants a true comparison between vehicle emissions, a life cycle analysis must be done that takes into consideration all these factors. Though the results may end up revealing that the electric car is still more efficient, the user will be surprised to find that the improvement is not as drastic as it at first appeared. Also as mentioned previously, life cycle analyses rarely take into account the disposal of materials. Especially in the case of electric car batteries, the future consequences of large scale disposal are for the most part unknown. Therefore, care must always be taken when comparing vehicle emissions. Whenever an emissions analysis is done and the data set includes both gasoline and electric vehicles, it is recommended that the GREET model be used for LCA or the MOVES and EMFAC models be used for Pump-to-Wheels analysis so as to provide consistency between outputs.

A last observation is that as technologies continue to increase the performance and functionality of vehicles, the need will arise to add another parameter to vehicle emissions models. This parameter will need to take into account the technology used, much like the EMFAC model has a "Technology Group" parameter.¹² This parameter will give reductions or additions to the emissions based on the technology used. By the addition of this parameter, developers will be able to rapidly adapt their models to incorporate new technologies.

6. CONCLUSIONS

This paper presented the most common technologies used to measure gasoline vehicle emissions and how vehicle emission models rely on these measurements to model and estimate vehicles emissions in real life conditions. The paper also presented a comparative synthesis between the major gasoline and electric vehicle emission models, including: 1) Macro-scale models: MOVES2014 and EMFAC; 2) Meso-scale models: VT-Meso, MOVES2014, and MEASURE; 3) Micro-scale models: VT-Micro and CMEM; and 4) Electric and gasoline lifecycle models: MOVES2014 and GREET. Furthermore, the paper highlighted common misconceptions associated with comparing emission estimates resulting from models that are based on different lifecycle stages, e.g. "well to wheel", "tank- or pump- to-wheel", or complete lifecycle models.

The observations and summaries in this paper are meant to be used as a beneficial introductory resource for researchers and users of vehicle emissions models. It is not comprehensive and only introduces the main processes involved in the models described above. This paper, however, presents an overview that would enable the reader to more easily comprehend the differences between these models and determine the model that would be best suited for a specific application. For a reader who is interested in learning about a specific model in more detail, this paper provides reference to many other publications.

A possible extension of this work, which the authors are currently pursuing, involves the simulation of a real-life network of intersections. This work would allow for a quantitative comparison between the estimates of various models belonging to different network scales (i.e. macro, meso, micro and LCA). This simulation takes into account both the scope and scale of the model and could be used to test the relative speed and accuracy of the models when estimating emissions.

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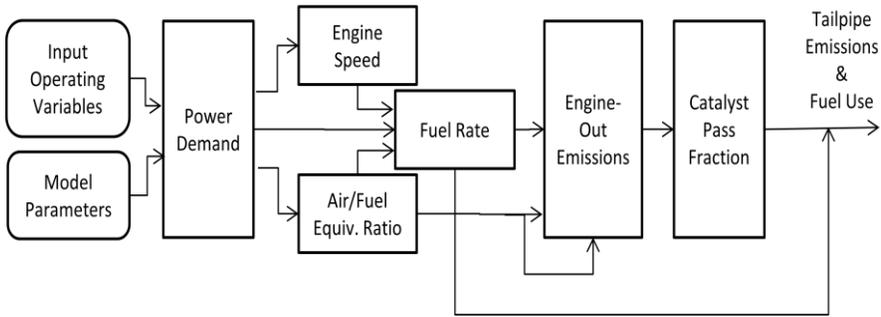


Figure 1: Simplified CMEM Model Process Flow Diagram ¹⁴

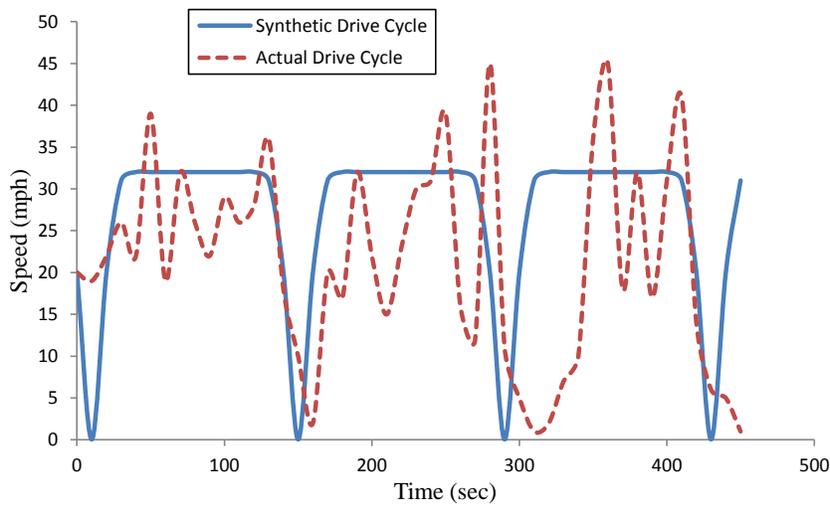


Figure 2: Synthetic drive cycle versus actual drive cycle for VT-Meso model (FWYF drive cycle)¹⁶

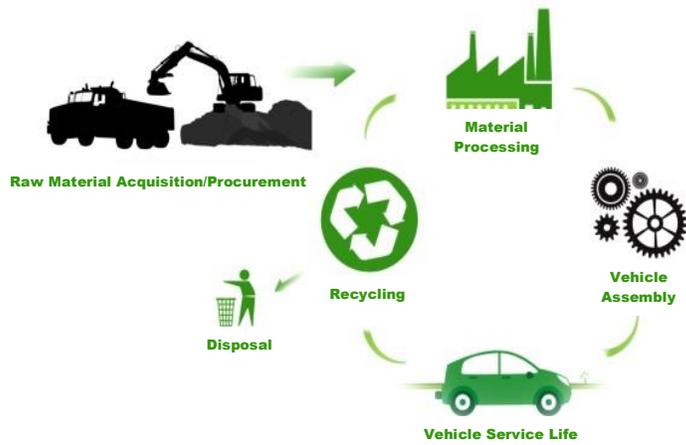


Figure 3: Life Cycle Analysis of Vehicles ¹⁹

Electricity Sources

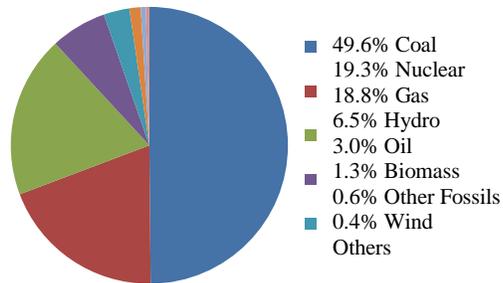


Figure 4: National Average of Electric Grid Distribution of Fuel Sources for United States ²¹

Table 1: Summary of Vehicle Emissions Models

Emissions Model	Energy Source	Scale	Significant Input Parameters	Strengths	Weaknesses	Best Use
MOVES 2014	Gasoline, Diesel, Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG), Ethanol (E-85), Electric*	Macro, Meso, Micro	Vehicle Miles Travelled, Road Type, Age of Vehicle, Speed Distribution, Meteorological Data, Vehicle Type, Fuel Type	Uses extensive database from which it draws information; Easy to use; Can use as a framework for other location specific models, allowing users to specify their own constants to be used when calculating emissions factors; Includes emissions estimates for a wide range of vehicle functions (e.g. hot soak, tire wear, idling, etc.)	Poor for situations in which there is highly variable accelerations and decelerations; Do not include life cycle analysis	Any "Pump-to-Wheels" analysis
EMFAC	Gasoline, Diesel, Electric*	Macro	Fuel Type, Technology Group, Model Year, Total Activity, Population, Vehicle Miles Traveled, Trips Generated per Day,	(See MOVES strengths above); Provides much more accurate emissions estimates for California projects as compared to the MOVES model	(See MOVES weaknesses above); Model developed using data specific to California	Any "Pump-to-Wheels" analysis in California
VT-Meso	Petroleum-Based	Meso	Average Vehicle Speed, Number of Stops made, Stopped Delays	Requires very few input parameters; Predicts HC, CO, and CO ₂ levels accurately; Less data and time intensive than micro emissions models	Is less accurate in situations where there are large amounts of speed variations or stop-and-go traffic	Projects in which a high level of accuracy is required, but the amount of collected data is limited.
MEASURE	Petroleum-Based	Meso	Vehicle Registration Data, Travel-Demand Forecasts of Flows, Speed and Acceleration Distribution Tables, Socioeconomic Data	Works extremely well with GIS database systems; Can also be used to predict congestion levels and distributions of modal activities; Statistical approach removes bias and can result in more accurate emissions estimates	Statistical approach may cause results to be vary slightly from past data	Scenarios involving GIS databases
VT-Micro	Petroleum-Based	Micro	Instantaneous Speed and Acceleration of Vehicle	Accurately predicts emissions for highly variable speed and acceleration situations ; Can be used with micro-simulation and traffic signal optimization software	Cannot take into account vehicle operating conditions such as deteriorated or malfunctioning equipment	In conjunction with micro-simulation software where the operating conditions of the vehicles makes little differences and where a high level of accuracy is required
CMEM	Petroleum-Based	Micro	Vehicle Speed and Acceleration, Road Grade, Engine Friction Factor, Cold Start Coefficients	Uses a physical, power-based approach that takes into account different vehicle operating conditions; Takes into account engine condition when evaluating emissions	Predicts constant emissions for deceleration events	In conjunction with micro-simulation software where the operating conditions of the vehicles are a concern and where a high level of accuracy is required
GREET	All	Life-Cycle	Fuel Source, Fuel Type, Fuel Transportation Pathway, Fuel Extraction and Vehicle Production Locations, Vehicle Miles Travelled	Uses life cycle analysis to predict emissions; Can evaluate a wide variety of vehicle types and fuel pathways; Easy to use; Best life cycle analysis currently available for vehicle emissions analysis	Is less accurate in the prediction of in-vehicle emissions; Can only provide rough estimates of emissions related to fuel extraction, transportation, and refinement; Does not cover recycling or disposal phases	Any "Well-to-Wheels" analysis

*Model estimates electric vehicle emissions using Pump-to-Wheels analysis only (See Section 4.2)